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THESIS

A MERCHANT SHIP SIZE OPTIMIZATION MODEL

by

Choi Ki-Chul

September 1983

Thesis Advisor: P. M. Carrick

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The theory of optimal ship size, a methodology for estimating scale economics, and the various factors affecting ship size are

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A Merchant Ship Size Optimization Model

by

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Commander, Republic of Korea Navy
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I. INTRODUCTION

This paper analyzes how a shipowner or a charterer as well as the industrial operator may determine the specification of optimal ship size for a given route with respect to certain market requirements. The selection of the vessel size as measured by cargo capacity is one of the most important decisions affecting the overall economics of a proposed ship in the preliminary designing stage.

Table 1 shows the increase in the number of larger-sized vessels in several categories during 1972-1978. The increased number of the large ships in 1978 ranges from one half times the number in 1972 for freighters of 13-15 thousand tons to over seven times for super tankers of over 300 thousand tons. From this table it may be seen that international seaborne shipping has utilized the bigger ships than the smaller ones while maintaining almost the same level of numbers in the lower categories.

What are the important factors underlying the increase in ship size in different types of ships? How does an owner use his own experience and cost data to determine the best ship size to maximize his profit? All these questions can be answered by the economic analysis based on his own cost data. The cost structures are different not only for the individual shipping agent, but also due to the type of shipping services and commodities.

TABLE 1

Changes in Ship Size of Major Merchant Fleet (over 1,000 GRT)

TYPES	SIZE 1,000 GRT	1972 number of ships	1972 total number	1978 number of ships	1978 total number
Freighters (general cargo, container ship, RO-RO, LASH ship)	under 7	5,953	12,029	7,037	14,140
	7-13	4,379		4,301	
	13-15	910		1,242	
	15 over	787		1,560	
Bulk carriers (bulk/oil, ore/oil, ore/bulk/oil)	under 40	2,787	3,539	3,356	4,651
	40-80	526		846	
	80-125	136		254	
	125-150	27		72	
	150 over	63		123	
Tankers (oil, chemical, liquid petroleum)	under 80	3,973	4,581	3,889	5,185
	80-150	298		548	
	150-200	37		79	
	200-250	198		319	
	250-300	67		292	
	300 over	8		58	
WORLD TOTAL			20,149		23,976

Source: A Statistical Analysis of the World's Merchant Fleets, U.S. Department of Commerce, 1972 and 1978.

The shipping services are categorized as liner, tramp, and industrial operation. Liner trades advertise scheduled service between the specified ports whereas the tramps do not. Industrial operations are captive services in which both ships and cargoes are controlled by a single entity. Ordinarily, company-owned fleets are sized below their owners' basic, continuing requirements, and the fluctuations in transport needs are met by charters from other owners.

For shipping purposes, commodities can be divided into four groups: major bulk commodities which are shipped in large volume like oil, iron ore, coal, and grain; minor or semi-bulk commodities which are loaded in smaller volumes, such as phosphate rock, bauxite and alumina, sugar, and salt; unitized cargo for container, Ro-Ro, and LASH ships; and general cargoes which are relatively small shipment sizes.

Gilman (1977) [Ref. 5] presented cost differences for various types of ships on a typical voyage. The range of the cost per day is from 7,628 dollars to 25,686 dollars shown in Table 2. These substantial variances are found in the costs of operating ship of various types, depending on the character of the ship itself, the trade in which it is employed, the flag of registry and the operating policies of the owner.

Since ocean shipping is a truly international business, ships are typically built wherever the most favorable arrangements can be made. They may be nominally owned by corporations,

TABLE 2

Daily Operating Costs ($), 1977

	14,600 dwt conventional ship	20,000 dwt Ro-Ro ship	23,400 dwt container ship
speed (knots)	14	22	22
capital cost	9.2 million	36 million	28.6 million
daily capital cost[1]	3,626	14,187	11,270
daily operating cost	1,828	3,081	2,937
insurance/day	202	930	770
crew wages & prov./day[2]	1,259	1,097	1,386
maint. & repair/day[3]	367	1,054	781
daily port cost	275	825	800
fuel in port/day[4]	275	825	800
daily sea cost	1,899	7,593	8,750
fuel at sea/day[4]	1,899	7,593	8,750
daily total cost	7,628	25,686	23,757

1. Calculated on an annuity over 18 years at 12% interest rate with 350 operating days per year.

2. Cost for European crews.

3. All geared medium speed diesels.

4. Fuel includes lubricating oil consumption.
Daily port cost includes only port fuel consumption.

Source: from Gilman's paper [5].

often holding a single vessel, which are formed solely for this purpose and domiciled wherever tax, registry, and national preference considerations may dictate. They may be managed by a professional manager, by a charterer, or by both, and they are operated by the best available crews under the law of the registered nation.

Under these complexities problems in deciding the optimum ship size will arise. The problems will be described in the next chapter.

II. GENERAL DESCRIPTION OF THE PROBLEM

For the shipowner the purchase of a vessel is very risky, due to the high capital investment, high expenses of operation, and the rapid technical progress in shipbuilding, as well as the fluctuation in market demand for shipping services.

Economic analysis should be carried out at the earliest planning stage, the so-called preliminary design stage. Figure 1 shows a simplified flow diagram of a ship design.

During the preliminary design stage of vessels, many technical and economic problems are faced. Technical problems are resolved by computer modelling on the basis of the builder's own experience but mainly, by an appeal to world experiences and the publicly documented results of past research work conducted concerning ship production and operation [Ref. 11].

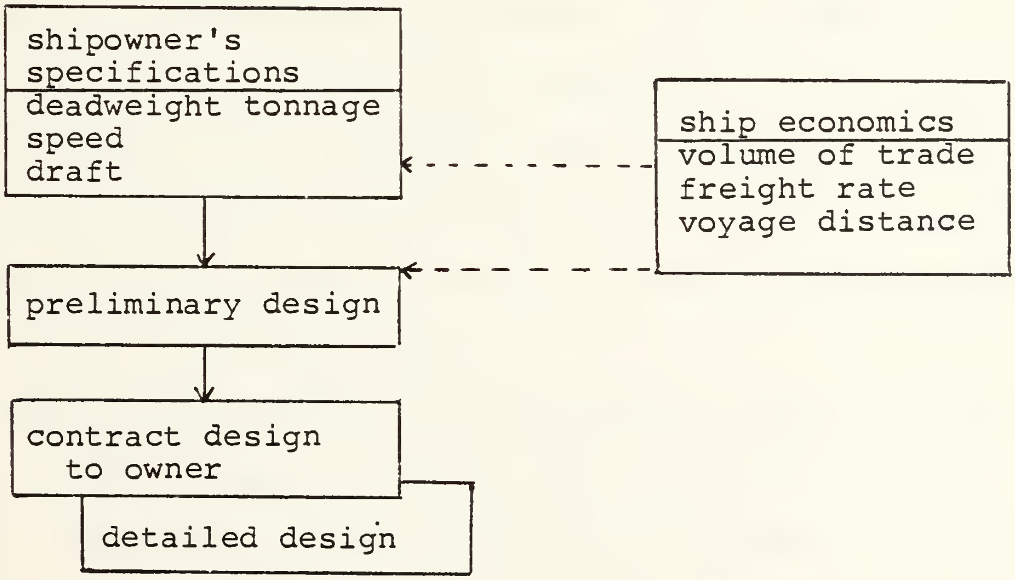

Figure 1. Simplified Flow Diagram of Ship Design

The matter of economic problems has, however, another facet. The ship research institutions working in various countries must work out for themselves their own model of ship economics, particularly in that part which concerns production technology [Refs. 4,6,8].

When modelling a ship's economics, it is necessary to identify the economic dependencies appearing in the process of production and operation of ships within a determined economic system.

This economic problem deals with the examination of the trade in which the ship is proposed by an owner. This examination may only be an analysis of existing ships of the same group in the trade in order to determine where improvements could be made and establish the economic relationship between factors by using scale economies [Ref. 8]. On the other hand, it may be a complete investigation of ship operating economics.

As far as the shipowner's economic calculations are concerned, the determination of the components of the costs, such as capital costs, operating costs at sea and in port over the economic life of the ship, is an important element. The basis of the shipowner's economic calculations are the results of the following data:

1. full characteristics of the shipping routes, such as,
    a. set of ports including canal and access routes;
    b. duration of one round trip corresponding to the ship's operation on the liner or tramp; and

    - c. expected number of the voyages per year based on the expected volume of trade
2. characteristics of the set of ports, such as,
    - a. average freight rate and value of the cargo carried;
    - b. canal charges en route before the port;
    - c. port charges and cargo handling rates in the port;
    - d. bunkering time in the port; and
    - e. unit cost of basic, light fuel, lubricant, and fresh water.

Using these previous sets of data, one determines costs for the required variants of ship operation.

The decisions about the type and size of the ship of interest to an owner need to be evaluated under a variety of market conditions since the uncertainty about future freight market conditions for the cargo liners will affect the decision policies. In the real world there is no possibility of performing comparisons between different forms of policies since the market conditions cannot be repeated for the convenience of experimentation. There is also the problem of the time-scale required as well as the financial risk involved.

In many shipping services, cargo availability is limited and ships in those trades are denied the economic benefits of larger ship sizes. This explains why general cargo liners seldom exceed 15,000 deadweight tons whereas tankers have grown to twenty times that capacity.

Because of the large range of possible designs which can be derived from a set of requirements, the economic modelling itself is of limited value without some method of selecting the best design--called the measure of effectiveness. The economic criteria, which provide the measure of effectiveness of a ship design, have been found by Benford (1968) [Ref. 1] and Goss (1968) [Ref. 6].

The cost model of this paper will not be used for the comparison of the several design alternatives, and will exclude physical constraints such as port depth and the market constraint which is randomly fluctuating over the planning horizon.

Chapter III provides a general description of scale economies in shipping industry in comparison with industrial plants, and a general review of the economic criteria for the optimum ship design and the theory of optimum ship size. Chapter IV presents the detailed optimal ship size theory, the estimates of scale coefficients, and the analysis of the factors influencing the optimum ship size. Chapter V gives the conclusions and recommendations.

III. LITERATURE REVIEW

The ship sizing problems with which this work deals is one of the applications of economic analysis to optimal policy decision-making. In most concrete applications, it is necessary to know specific parameters describing agents' behavior. The scale economies refer to a long-run planning time horizon over which all inputs may be varied. A review of the economies of scale and the cost functions to represent the relationship by defining the simplified input and output factors for the above parameters will be presented. The second section of this chapter describes economic criteria for optimizing ship design by Goss [Ref. 6] and Benford [Ref. 1]. The third section discusses the various approaches to decide the optimal ship size by using cost models of Kendall [Ref. 9], Jansson and Shneerson [Ref. 8], and Benford [Ref. 2]. The last section provides a comparative summary of the three optimization models.

A. SCALE ECONOMIES OF SHIPS

Economies of ship size have in the 1970's been held up as the salient feature in modern shipping [Ref. 8]. The size of ships has been increasing very rapidly, leading many observers to believe that no limit exists for the optimal size and that there are only exogenous constraints, such as restricted port depths and market conditions.

To gain some perspective on the issue of ship size economies, the general issue of economies of industrial plant sizes will be reviewed.

Haldi and Whitcomb's cost studies [Ref. 7] present evidence derived from engineering data on economies of scale in manufacturing and processing plants. The engineering approach was used in their paper since the actual data on the construction and operating costs of industrial plants are usually closely held. Other reasons why accounting data may not yield reliable estimates of scale economies were discussed in their paper.

The engineering cost studies point to practically unexhausted economies of industrial plant size, with the main factor limiting the growth of plant size being the market size, or distribution costs. In general, constant production economies of scale is the likely ultimate result. As far as pure production is concerned, "the biggest is also the best up to a certain output" [Ref. 8].

This principle is convincingly illustrated by Haldi and Whitcomb [Ref. 7]. Using data collected from a large number of engineering cost studies of industrial plants, they calculated the elasticities of capital costs and labor costs with respect to output capacity, or "plant size", by fitting a function of the geometric form:

$$C_i = a_i H^{b_i} ,$$

where H is plant capacity, C_i, a_i, and b_i are i^{th} factor costs, a constant and the scale coefficient, respectively.

The majority of Haldi and Whitcomb's 221 different estimates of capital cost elasticities fall in the range 0.6-0.8. This can be explained mainly by a family of geometric relationships that relate the material required for the building of equipment to the capacity of this equipment. The amount of material required to build containers depends on the surface area, whereas container capacity depends on the volume enclosed. However, they found that the principle source of plant size economies is the saving in labor costs. Of the 53 estimates for the elasticity of labor costs, 71 percent took values below 0.4. There is no simple, neat geometric rationale for this. It just appears that big plants are markedly labor-saving [Ref. 8].

Does this general picture of plant size economies apply to shipping? At first glance the geometric relationships that account for economies of ship size and the saving of crew costs seem to apply to shipping.

Jansson and Shneerson [Ref. 8] point out that in general cargo ships there are offsetting diseconomies to ship size; namely, the loading and unloading of cargo which are characterized by inherently diminishing returns to ship size. Their paper concludes that the optimal ship size in shipping is determined from a tradeoff between ship size economies at sea and size diseconomies in port.

Kendall [Ref. 10] indicates that the existence of economies of scale in shipping has long been known and that, for a given annual tonnage of freight to be carried, the longer the sea voyage the more these economies can be utilized. He uses the bulk cargo ships as the basis for his optimal ship size theory.

Benford [Ref. 2] also used the geometric functional forms as in Jansson's model except he used several different independent variables. The variables considered were the material weight, shaft horsepower, speed, and a volumetric displacement measure (cubic number) in addition to the ship size, i.e., deadweight tons, whereas Jansson's model used only the ship size as an independent variable.

Benford established a detailed technique for investigating the economic performance of alternative designs in various route environments such as the cargo availability. In this sense, the models of Jansson and Kendall can be regarded as submodels of Benford's profit maximization model.

Chappel [Ref. 8] points out some difficulties as follows:

> Although it is necessary to be aware of the input and output relationships in ship building, it is not possible to incorporate the form of complex technical parameters in the analysis. They are set to one side in an approach embodying the 'black box' concept of operations research, in which the relationship between complex systems is examined without going into detailed operation.

However, it is fairly well established in the literature that for some inputs, such as daily fuel costs, the functional

form is Cobb-Douglas (that is, log-linear). Thus,

$$C(S,V) = aS^{\alpha}V^{\beta} ,$$

where C(S,V) is the function of the size, S and speed, V, and the positive constants a, α, β.

The other cost functions such as the operating or capital cost functions are less clear-cut. No particular functional form has received broad acceptance in the literature and, for this reason, the following alternatives can be considered:

$$C(S,V) = aS^{\alpha}V^{\beta} \tag{1}$$

$$C(S) = aS^{\alpha} \tag{2}$$

$$C(S,V) = a + bS + cV \tag{3}$$

where a, b, c are positive constants and α, β are the scale coefficients. Equation (2) is, of course, merely a bivariate restriction of Equation (1).

Benford [Ref. 4] uses the arithmetic sum form like Equation (3) with variables such as shaft horsepower, a volumetric displacement measure as well as the speed and size of the ship in his estimated cost functions for the general cargo and bulk cargo carriers.

Jansson and Shneerson [Ref. 8] use the form of Equation (2) for all cost functions in the general cargo and bulk

cargo ships. Chappel and Ryder [Ref. 8], and Johnson and Garnett [Ref. 9] use the same function for the capital and operating cost in their analysis of container ships.

Further discussions about the specific cost model from using the formula (2) will be described in Chapter IV.

B. ECONOMIC CRITERIA FOR OPTIMAL SHIP DESIGN

It is assumed that the shipowner is interested in maximizing his profits, therefore, he is interested in the most profitable ship design. There are generally several different ways of designing a ship. Yamagata and Akatsu's tanker design (1964), Murphy, Sabat, and Taylor's general cargo ship design (1965) as well as Benford (1968), Mandal and Leopold's general cargo ship and tanker design (1966), and other methods have been introduced in the literature [Ref. 11].

All of them may be internally consistent and technically feasible but it is likely that one method will perform better than the others. Not only do we have many different types of engine and hull shapes to choose from, but any given flow of cargo can be carried in ships of different sizes and numbers, offering different service frequencies and, possibly, different sea speeds and turn around times. In addition to these fundamental elements of ship designs there are many minor decisions such as the selection of the type of crane, how many to have, and their locations.

This section will present the much more elemental one of offering a criterion as the measure of effectiveness which takes all aspects of the alternative designs into account and enabling them to be compared.

Benford [Ref. 1] points out that economics considerations are something of a universal solvent, allowing the engineer to weigh the relative merits of design alternatives involving different units such as a choice between two engines, one heavier but more compact than the other, involves both weight and volumetric units. Converting the costs of both units to resulting present and future costs allows rational quantitative judgment. Thus, Benford concludes that a good architect, then, must know how to make economic studies and must develop his ability to estimate future building and operating costs. The final proposal to the prospective shipowner is presented in terms of profitability. Then, how do we measure the economic efficiency of the ship that a shipowner may contemplate building? What should be the criterion for comparing ship design alternatives?

The net present value criterion was used by Goss (1968) [Ref. 6], not only for determining which of two or more alternatives should be selected, but whether any of them should be built at all; and if so, whether the construction should be started now or postponed until some future date. This criterion is applicable to liners, tramps and tankers.

Goss [Ref. 6] suggests the following criteria:

1. What will be the gross benefits over the ship's economic life? In the simplest case this is the gross earnings of the ship. But where the ship is operating as part of a liner service then there may be some effects on the earnings of other ships in the same ownership and these must be taken into account. Either way, the figure the shipowner needs is the difference between what the revenue would be with the investment and what it would have been without it?
2. What is the cost of the ship? This can be divided into two parts:
    a. Initial costs as capital costs may include some elements which an accountant would not normally recognize as capital such as the special training for the crew or the stand-by senior officer during the building period.
    b. Operating costs include fuel, wages, store and provisions, insurance, maintenance and repair, port charges, etc.
3. What is the economic life of the ship, either where the alternatives are to scrap the ship or to sell it? Because the second-hand values are usually based on the estimated profitability of the remaining ship's life, the final decision preferring one to the other will not make much difference except for highly

specialized ships. It is usually assumed that all ships are retained until scrapping.

4. What is the distribution of estimated revenues over the estimated life? The distribution of earnings throughout the ship's life cannot be assumed to be constant. In addition, any rising or falling trend in the supply-demand position for the type of ship under consideration may affect the freight rates and the load factors in the liner trades.
5. What is the distribution of the estimated operating costs over the ship's expected life? The operating costs may also rise or fall over the life of the ship.

Goss shows that the answers to all these questions can be stated in terms of time and money such as Net Present Value, but with some practical difficulties. The difficulties are the general shortage of cost data, no indication of short-run opportunity cost, and differences between operating individual ships and operating a fleet.

On the other hand, Benford [Ref. 3] and Nowacki [Ref. 11] present five ways to express profitability of the investment for the comparison of ship design alternatives:

1. Capital Recovery Factor

$$CRF = \frac{A}{P}$$

where $A = R-Y$ is average annual returns*, R is the average annual revenues over the economic life of a ship, Y is average annual operating costs, and P is the invested costs.

CRF is of usefulness only where revenues are predictable, returns are uniform, and the length of lives for alternative ship designs are equal. This criterion would choose the alternative with the highest value of CRF.

2. Returned Interest (or Yield)

$$R = CR \cdot P$$

where

$$CR = \frac{r(1 + r)^n}{(1 + r)^n - 1}$$

is the capital recovery factor for given life of a ship (n years) and the owner's interest rate, r, P is the investment.

When the predictable revenues and costs are known but the lives differ between alternatives, this is a good measure of profitability. The CR can be converted to an equivalent rate of return.

3. Net Present Value Index

$$NPVI = \frac{NPV}{P}$$

where

$$NPV = \sum_{i=0}^{n} A_i (1 + r)^{-i} - P$$

---

*Before-tax and after-tax for all criteria were not used for simplicity.

regarding all cash flows which include the annual returns in year i as A_i, the initial capital cost as P, the life of the ship as n and the interest rate as r.

This is more useful than the NPV criterion since the highest net present value may mislead the decision maker when the capital is limited because he tends to favor the bigger investment.

4. Average Annual Cost

$$AAC = Y + CR \cdot P$$

where Y is the annual operating costs, CR is the same as the second criterion and thus CR·P is the annual cost of capital recovery to the investment P. This criterion is useful where revenues are unknown and approximately the same for all designs.

5. Required Freight Rate

$$RFR = \frac{AAC}{C}$$

where AAC is the average annual cost, C is the annual transport capacity, in deadweight tons.

This is a measure of benefits where revenues are unknown and cannot be assumed to be the same among design alternatives because of differences in transport capability. The alternative with the lowest RFR is desired. In the bulk trades where cargo is relatively unlimited, different possible

ships may promise varying annual transport capabilities. In such cases the NPV and AAC criteria mislead the decision making. This RFR is the rate that the shipowner must charge his customer if the owner is to earn some reasonable return on his investment.

This criterion can be used to find the minimum required freight in the cost model of this paper as a guide to the expected minimum required rate for a specified ship.

The advantage of having a single measure of effectiveness is that it facilitates the overall modelling for optimization studies by computer. The use of optimization methods in ship design has proved very valuable in the literature [Refs. 2,11].

In the next section the theory of optimization for the selection of ship size will be reviewed.

C. THEORY OF OPTIMAL SHIP SIZE

Of the general problem of optimizing ship design, the subproblem of optimizing ship size has received the largest share of attention in the literature. Some of the contributions are Benford (1968), Heaver (1968), Ericksen (1971), Goss (1971), Kendall (1972), and Jansson (1978) [Ref. 8]. This concentration of analysis may be explained by the fact that other design variables exhibit little variation once the size of a ship is fixed. On the other hand, the wide variations in ship sizes between different types and the tremendous growth in ship sizes of all types during the last

two decades has stimulated researchers to look for a systematic explanation of the factors influencing the size of ships.

If the cargo base is large enough not to impose a constraint on the choice of ship design and frequency of shipping service is enough for changes to have little effect on the costs of shippers, the optimal ship size for a particular route is defined, by Kendall [Ref. 10], and Jansson and Shneerson [Ref. 8], as that which carries cargo of a given composition at the lowest total transport cost to the shipowner per cargo ton in the long run. This criterion will not necessarily be the same as minimum cost over the economic life of the ship if the unlimited cargo availability and the effective operation by the shipping operator are not assumed. Based on the limited cargo availability and/or other predicted fluctuations such as seasonal effects, Benford [Ref. 2] defines the optimal ship as the one that has the lowest Required Freight Rate under the assumption of a constant freight rate over the life of the ship in his paper.

The basic costs are composed of the capital costs, and operating costs at sea and in port in the models of Benford, Kendall, and Jansson and Shneerson although the detailed components of each cost category are different for each model. The detailed cost components will be examined in Chapter IV.

Kendall [Ref. 10] suggests that the volume of trade, length of route and value of the products are the primary determinant of ship size and sailing frequency to a port. Kendall asserts that the ship-based investment for the development, operation, insurance and servicing of large oceangoing vessels is now being approached by the port-based investment for the cargo handling, storage, and the harbor works to accommodate them.

Kendall's model, especially, accounts for the effects on costs of cargo composition and storage under assumptions which will be outlined in the next section. The economies of the size at sea always exist whereas the port economies are not simple functions of the stocks of product held on the quayside.

If the capital investment and other holding costs of these stocks are included, a realistic balance is found to exist, depending not only upon the volume of product but also upon its value. This is one reason that the lower value of the product such as coal, iron ore, or grain are carried in the larger bulk carriers. Based on Kendall's model, the appropriate size of the ship should change annually on most routes. This would militate against ownership of the vessel by the shipper or receiver, but would encourage chartering.

The theory of Kendall's model does not concern itself with the optimum ship size in the sense of capacity, but is concerned with the trading requirements of specific routes

carrying certain products particular distances whereas only the cost function of ship's time was used as Jansson's model. Thus the port is in a much stronger position to determine its future requirements of channel depths, quay and lock capacities, and quayside storage capacity for bulk cargo with consideration of macroeconomics in the shipping industry.

Jansson and Shneerson [Ref. 8] use a long run cost and a production model derived from marine engineering principles to establish the economies and diseconomies of the ship size. Their estimates of the scale coefficients were obtained by the application of the regression technique with cross-sectional accounting data.. This model uses a geometric relationship between capacity and ship size, and between costs and ship size based on Thorburn's engineering study (1960) [Ref. 8]. The study of Goss [Ref. 6] and others for the time cost of the ship supports the estimates of Jansson's model.

This model can be used for general cargo and dry bulk carriers in the liner trades, but can be applied for container ships and tankers with different values of the parameter. In fact Johnson and Garnett (1971) [Ref. 9] use the same functional form as Jansson's model for capital and operating costs, except fuel cost, in container ships.

Benford's model [Ref. 2] for general cargo ship allows for the selection of the most economical general cargo liner by the measure of effectiveness, RFR. This model evaluates the RFR under various circumstances such as seasonal

fluctuations, constant long term availability of cargo, various conditions of voyage, and high sea speed.

D. SUMMARY

Table 3 summarizes the ship size optimization models which have been discussed. It is noted that there is no uniquely accepted model of ship size optimization since each shipowner or shipyard has various cost structures to produce and operate a certain type of ship. Thus, in the remainder of this paper, attention will be restricted to the optimal ship size based on Jansson's approach under the known route characteristics and unlimited cargo availability.

TABLE 3

Summary of Ship Size Optimization Models

Authors	Ship Type	Typical Assumption	Basic Theory	Typical Conclusions
Benford (1968)	General cargo ship	1. considered various market conditions in the long run 2. cargo handling cost excluded 3. multiport visit per round trip	scale economies based on engineering principle with multi-independent variables and physical constraints	1. ±20% size of the optimum ship size has the profitability within 2.5% of the max. level of profitability. 2. Cargo availability is the most significant effect to the optimum size.
Kendall (1971)	Bulk cargo carrier	1. unlimited cargo availability 2. none onboard handling equipment 3. short-run cost model 4. constant turn around time in port	scale economies based on the macroeconomics for port investment	1. Combined effect of ship production, operation and port industry determine the optimum ship size.
Jansson & Shneerson (1982)	General cargo/ bulk cargo carrier	1. more than 80% cargo availability 2. long-run cost model	scale economies based on engineering principle with single independent variable	1. The combined effect of ship production, operation and route characteristic determine the optimum size.

IV. PROBLEM APPROACHES

A. FORMULATION OF THE PROBLEM

To create the maximum possibilities for making economic profits involved in the future production and operation of the ship, the optimal size of the ship can be determined by minimizing total lifetime costs per ton at sea and in port.

To minimize the total costs per ton in every aspect of shipping service, the objective function must be the total cost function which relates the size of the ship to specified route characteristics and market constraints. If the market condition can be assumed to be constant and enough cargo is available, then the problem is to find the economical ship size with minimum total transport cost per ton at sea and in port.

The two distinct measures of a ship's output are defined for this objective as:

> The handling capacity (H_1), which equals the amount of cargo that can be loaded into or discharged per unit of time . The unit of measure of H_1 is deadweight tons loaded or unloaded per hour.
>
> The hauling capacity (H_2), which equals the size of the ship that is the holding capacity (H_0), multiplied by ship speed (V). The unit of H_2 is used as deadweight ton-miles per day. The hauling capacity can be defined as:

$$H_2 = H_0 \cdot V \tag{4}$$

Total costs per deadweight ton are composed of two separable parts, costs per ton at sea and costs per ton in

port. For this a complete output of shipping service must include the loading of a cargo at a port i, the hauling from the port i to port j, and the unloading of the cargo at port j.

By this approach the total transport costs can be divided into two main categories: so-called ship's time costs or time-proportional costs and cargo costs. The cargo costs are by and large proportional to the quantity of cargo [Ref. 8]. A miles-proportional cost which relates to the voyage distance, such as the fuel cost at sea, can be regarded as the time-proportional cost at a given speed. The time costs incurred per day at sea and in port are not of the same nature. The cost of fuel is the most important cost only at sea and lay-time proportional port charges are only in port whereas some of the operating costs, such as the crew wages are related both at sea and in port.

For the notational convenience the factor costs incurred only in port are ordered from 1 to k, those that are incurred both in port and at sea from k+1 to n, and those incurred only at sea from n+1 to u. Therefore the total time costs at sea and in port, and total cargo costs can be defined as follows:

Total time cost per day in port (TC_1):

$$TC_1 = \sum_{i=1}^{n} f_i(S) \qquad (5)$$

for $i = 1,\ldots,k,\ldots,n$.

Total time cost per day at sea (TC_2):

$$TC_2 = \sum_{i=k+1}^{u} f_i(S) \tag{6}$$

for $i = k+1,\ldots,n,\ldots,u$.

Total cargo cost per ton of cargo (TC_3):

$$TC_3 = \sum_{i=1}^{k} g_i(S) \tag{7}$$

for $i = 1,\ldots,k$, where S is the ship size in deadweight tons, $f_i(S)$ is the function that relates time costs to ship size, and $g_i(S)$ is the i^{th} cargo cost per ton.

To transform daily port costs to costs per ton, divide TC_1 by the handling capacity in tons loaded/unloaded per hour H_1, and multiply by effective working hours per day p. The resultant cost should be multiplied by two, since each ton of cargo is handled twice in both ports to obtain the handling cost per ton.

Handling cost per ton in port (C_1):

$$C_1 = \frac{2 \cdot TC_1}{pH_1(S)}$$

$$= \frac{2 \sum_{i=1}^{n} f_i(S)}{pH_1(S)} \tag{8}$$

Similarly the daily sea costs can be transformed. Divide TC_2 by the hauling capacity in ton-miles per day H_2, and the

cargo balance factor ℓ. This yields the costs per cargo ton-mile. Then this is multiplied by the round trip distance D miles to get the hauling cost per ton of cargo on the specified route.

Hauling cost per ton at sea (C_2):

$$C_2 = \frac{D \cdot TC_2}{\ell H_2(S)}$$

$$= \frac{D \sum_{i=k+1}^{u} f_i(S)}{\ell H_2(S)} \qquad (9)$$

where the cargo balance factor ($1 \leq \ell \leq 2$) is defined as

$$\ell = \frac{\text{total volume of cargo on both legs}}{\text{volume of cargo on the fat leg}} .$$

Clearly, the cargo cost per ton increases linearly with the increasing of the size of the ship because the more-carried products need more spaces, so that the investment in the quay side and the interest cost for the cargo must be increased. Thus,

$$C_3 = \sum_{i=1}^{k} g_i(S) \qquad (10)$$

The total cost per ton of cargo becomes:

$$TC(S) = C_1(S) + C_2(S) + C_3(S) \qquad (11)$$

Shipbuilding and marine engineering cost studies [Ref. 8] have shown that a geometric function is the most suitable form for expressing the relationship between handling and hauling capacities, and costs to the size of the ship.* This model includes design parameters H_0, H_1 and V which are too ambitious in view of the limited knowledge of the relationship between ship design and shipping costs. However, a simplification is afforded by reducing the many design parameters to the most important one--the holding capacity which is the ship size. Then the two capacities can be written:

$$H_1 = h_1 S^{E_1} \tag{12}$$

$$H_2 = h_2 S^{E_2} \tag{13}$$

where h_1 and h_2 are design parameters that vary among ship types. E_1 and E_2 are the output elasticities of two capacities with respect to ship size. The proportionality coefficient h_1 is different across ship types and varies by exogenous factors, such as cargo composition, port capital and labor productivity. Likewise, h_2 is a design parameter which relates to a stowage factor that varies by ship types

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*Shipping factor costs on the basis of marine engineering principles and testing of this relationship statistically emanates from Thorburn's study, Supply and Demand of Water Transportation, the Stockholm School of Economics, 1960. Jansson and Shneerson extended the relationship in "The Design of Liner Shipping Service", Maritime Policy and Management, v. 9, no. 3, 1982.

The i^{th} factor cost per day, $f_i(S)$, which relates the ship's time costs can be defined:

$$f_i(S) = p_i q_i S^{e_i} \tag{14}$$

for i = 1,...,k,...,n,...,u, where p_i is the i^{th} factor price and $q_i S^{e_i}$ represents the i^{th} factor requirement per day.

Substituting the Equations (12) through (14) into Equations (8) and (9), the total transport costs per ton for D nautical miles of a round-trade route are:

$$TC(S) = \frac{2 \sum_{i=1}^{n} p_i q_i S^{e_i - E_1}}{p h_1} + \frac{D \sum_{i=k+1}^{u} p_i q_i S^{e_i - E_2}}{\ell h_2}$$

$$+ \sum_{i=1}^{k} p_i q_i S^{e_i} \tag{15}$$

for i = 1,...,k,...,n,...,u factors.

The optimum ship size can be found by minimizing the total costs per ton in port and at sea, TC(S) under the given assumptions.

B. ESTIMATES OF THE SIZE ELASTICITIES

The hypotheses on elasticities are based on marine engineering principles. These estimates have been computed by Thorburn (1960), Heaver (1968), Goss and Jones (1971), and Jansson and Shneerson (1982) [Refs. 6,8] by using the following technical principles.

1. Output Elasticities, E_1 and E_2

Based on the above assumption, handling capacity (handling speed) is proportional to the length of the ship. Since the dimensions of the ship, such as length, beam, and draft, are in constant ratio to one another, the handling capacity H_1, becomes proportional to the 1/3-power of ship size [Ref. 8].

$$H_1 = h_1 S^{1/3}$$

where S is the deadweight tons of a ship and h_1 is a proportional constant depending on a particular ship type.

The relationship between handling capacity and ship size was estimated by applying regression analysis on cross-sectional data.

Handling speed, H_1 can be written as:

$$H_1 = \frac{S}{T} = aS^{1-b}$$

if $T = aS^b$ is the time spent in port and a, b are estimated by the log-linear form as in Table 4. Table 4 shows that $E_1 = 1-b$ has the values from 0.19 to 0.24, so that this supports the 1/3-power rule.

The elasticities of handling capacity based on the empirical results in a typical port is not a conclusive one since the time in port may be affected by random components, such

TABLE 4

Regression Results of Times in Port on Size by Jansson

$$\log T = \log a + b \log S$$

data type	log C	b	R^2	E_1	Range of E_1
A	0.362	0.76 (0.1)	0.28	0.24	$0.1 \leq E_1 \leq 0.33$
B	-0.783	0.808 (0.107)	0.54	0.19	

Sources:

A. Sampled from fully loaded citrus fruit cargo ships in Haifa and Ashdod, Israel during 1969-1970, 156 observations* of 17 different sizes of vessel from Shipping Report, The Israel Citrus Marketing Board.

B. Sampled from 80% dwt loaded general cargo ships in Haifa in 1972, 122 observations from Statistical Report of Haifa Port Authority.

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*Each arrival is taken as one observation. Homogeneous commodity was chosen to exclude variations in handling speed by type of commodity. The number in parentheses are the standard deviations.

as port congestion, strikes, and some political action. This is the reason why the general formula between handling capacity and ship size might not be accepted across all countries in the shipping world. However, the author accepts this formula. The "1/3-power formula" was confirmed by the samples of Jansson and Shneerson, and 1/3 can be taken as an upper limit of the size elasticity.

To determine an optimum ship for a specific purpose, the handling size elasticity must be measured individually by a shipowner and Equation (12), $H_1 = h_1 S^{E_1}$ can use $0.1 \leq E_1 \leq 0.33$. The standard error of the estimates was considered to select this range.

A high design speed is very costly, both in terms of required horsepower and in terms of fuel consumption. However, to achieve a certain speed the required horsepower is less than proportional to ship size, so that the hauling speed is expected to increase with ship size for a proportional change in horsepower. This phenomenon can be explained by the principle that the resistance of water against the ship's hull does not increase at the same rate as the volume of the hull. According to a naval architect's rule of thumb based on the Thorburn's study (1960), the design speed should increase by the square root of the length of the ship. In shipbuilding, this old rule-of-thumb is called the "inch-rule" which implies design speed is a function of deadweight tons to the power of $1/6 \simeq 0.16$.

The inch-rule formula was tested on the samples in Table 5. The general cargo, container ships and bulk cargo carriers sampled from World Ships on Order (1980) seem to follow this

TABLE 5

Regression Results of Speed on Size

$$\log V = \log a + b \log S$$

Data Type	Log a	b	R^2	E_2	Range of E_2
A	1.3	0.16 (0.04)	0.42	1.16	
B	1.2	0.16 (0.026)	0.54	1.16	
C1	0.68	0.13 (0.051)	0.40	1.13	$1.0 \leq E_2 \leq 1.2$
C2	0.4	0.2 (0.046)	0.72	1.2	
C3	0.92	0.06 (0.028)	0.29	1.06	

Sources:

A. Sampled from World Ships on Order, Feb. 1975. 50 observations by Jansson.

B. Sampled from 34 bulk cargo ships of Zim Nav. Co., Feb. 1976 by Jansson.

C. Sampled from World Ships on Order, Feb. 1980, by author. C1 is 50 dry cargo ships, C2 is 50 container ships, C3 is 30 dry bulk carriers.

rule, but the dry bulk cargo ships do not yield a correlation between the design speed and ship size. Generally the bulk cargo ship mainly has the speed range from 12 up to 16 knots whereas the general cargo or container ships have 12-22 knots. E_2 of the bulk cargo ship can be taken as the lower limit of the size elasticity.

The hauling capacity, H_2 can be written as:

$$H_2 = SV = aS^{1+b}$$

if $V = aS^b$ is the design speed and a, b are estimated by the regression technique. Similarly, hauling size elasticity from the inch-rule formula can be measured and Equation (13), $H_2 = h_2S^{E_2}$, can use $1.0 \leq E_2 \leq 1.2$.

2. Cost Elasticities, e_1-e_4

Based on the Benford [Ref. 3], Kendall [Ref. 10], and Jansson [Ref. 8] models the transport costs are composed of four categories: (1) capital cost is an annuity of purchase cost of the ship; (2) operating costs include the crew wages, stores and provisions, insurance, and maintenance and repairs; (3) fuel costs for the propulsion machinery at sea; (4) cargo costs include the insurance of the cargo, its interest during the voyage and its storage costs in port for the cargo carried.

Table 6 presents the estimated cost elasticities from the study of Thorburn (1960), Getz et al (1967), Heaver (1968),

TABLE 6

Elasticities of Costs with Respect to Ship Size

Ship Type	Capital Cost (e_1)	Operating Cost (e_2)	Fuel Cost (e_3)	Cargo Cost (e_4)
Tramps (Thorburn)	.67	.4	1.0	
Liner (Getz et al)	.6	.6		
Dry Bulk Carrier (Goss et al)	.7	.4	.8	
Dry Bulk Carrier (Jansson et al)	.655	.43	.72	1.0
Dry Bulk Carrier (Gentle et al)	.603			
Container (Gentle et al)	.853			
Tanker (Heaver)	.6	.3	.6	

Goss and Jones (1971), Jansson and Shneerson (1978), and Gentle and Perkins (1982)* [Refs. 6,8].

a. Capital Costs

The main components of capital cost are the hull and the propulsion machinery. The hull cost is divided into

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*Not available whole results from An Estimate of Operating Costs for Bulk, Ro-Ro, and Container Ships, information paper 4, BTE, Canberra, 1982.

hull structure, outfitting, and hull engineering costs. Capital costs might be underpriced in the early years of a new system, such as containership, partly because of underestimation in ship building costs and a desire by shipbuilders to gain a recognized place in an important new market. This can result in heavy losses, as has occurred recently in South Korea.* The long-run opportunity cost of the capital investment was used as the economic measure of the cost of ship's time. Thus the capital charges were taken from an annuity equivalent to the capital cost of the ship and extending over its life. The rate of discount employed in the analysis is usually 10 percent, but the average historical rate of return of a shipowner or minimum desired rate of return might also be used.

Based on the above considerations Benford (1968) [Ref. 4] has estimated the size elasticities of the labor inputs from 0.75 up to 0.8 with respect to the steel weight in hull construction. Ericksen (1971) [Ref. 8] quotes that size elasticities of material weights with respect to ship size exceed 0.8.

Jansson and Shneerson (1978) [Ref. 8] use the shipbuilding rule of thumb which makes the horsepower (HP) proportional to the 2/3-power of the ship size multiplied by

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*"The Koreans and Japanese are making life diffulct both for themselves and everyone else by cutting prices as much as 25% for new ship construction," from The Wall Street Journal, 30 March 1983.

the cube of the design speed as far as the propulsion machinery is concerned. That is, $HP = aS^{2/3}V^3$, where a is the positive constant.

Given the speed, the cost savings in horsepower per deadweight ton can be realized by the decrease in construction costs of the machinery per unit capacity. According to Chapman (1969) [Ref. 8] the elasticity of the capital cost of a diesel engine with respect to the brake horsepower equals 0.614. Benford (1968) [Ref. 4] gives a formula in which the capital cost for the machinery is proportional to the shaft horsepower raised to 0.6 power.

The "2/3-power rule" for the shipbuilding rule of thumb was confirmed by Jansson and Shneerson (1978) [Ref. 8] as in Table 7. Recently Gentle and Perkins (1982) have estimated the size elasticity of capital cost for the containerships as 0.853. This can be used as an upper limit of size elasticity of capital cost in the model. Therefore, the size elasticity of the capital cost with respect to ship size has a range of $0.6 \leq e_1 \leq 0.85$.

b. Operating Costs

The operating costs consist of the crew wages, insurance, maintenance and repair, and port costs including canal dues. The port costs have been considered as an operating cost or have been assumed to be zero since the costs of port services is continually changing and it is difficult to establish the functional relationship. Goss [Ref. 6] discussed

TABLE 7

Regression Results of Costs on Size by Jansson

$$\log C = \log a + b \log S$$

Factor Cost	log a	b	R^2	e_1-e_4	range
Capital Cost, \$/day^1	0.627	0.655 (0.088)	0.34	0.655	$0.6 \le e_1 \le 0.85$
Operating Cost, \$/day^2	1.61	0.43 (0.09)	0.41	0.43	$0.3 \le e_2 \le 0.6$
Fuel cost \$/day^2	0.796	0.72 (0.07)	0.74	0.72	$0.6 \le e_3 \le 1.0$
Cargo (port) Cost, \$/day				1.0	$e_4 = 1.0$

Sources:

1. Capital costs, sampled from Shipping Statistics and Economics, H.P. Drewry Ltd., 50 dry bulk carriers built in 1976/1977.
2. Operating and fuel costs, sampled from the Zim Nav. Co. (Israel) accounts of 34 ships in 1976.
3. The result of the regression was not given in the Jansson's model except the e_4 value.

in detail the difficulties to compute these time-related costs, but the concept of long-run opportunity cost of a ship's time was used. In addition to that the crew costs are usually assumed to rise at a rate of 3 percent in real terms relative to other costs. The rate of discount for annual operating costs can be taken as well as the capital cost.

Benford (1968) [Ref. 4] estimated the cost of deck crews, which is proportional to the ship size raised to the 1/6-power, and the cost of engineering crews, which is proportional to the 1/5-power. Ericksen (1971) [Ref. 8], however, gives the elasticity of the crew with respect to ship size as 0.1 for container ships and 0.03 for tankers. Jansson and Shneerson (1978) [Ref. 8] confirmed that the size elasticity of crews is of little importance, such as 0.03 in the dry bulk carriers.

The size elasticity of maintenance and repair costs is the same as that of the capital cost according to Jansson and Shneerson (1978)[Ref. 8]. Benford (1968) estimates the maintenance and repair costs which are proportional to the ship size raised to the 2/3-power.

The size elasticity of insurance is higher for very large ships than for ships of moderate size. Benford (1968) [Ref. 4] uses a formula where the cost of insurance is proportional to the amount of capital costs. Gentle and Perkins (1982) point out a difficulty in modelling this cost

because of variations in the profitability of the market, in the commodity carried as cargo and the route, or in the insurance coverage. Ericksen (1971) [Ref. 8] estimated 0.7 as the size elasticity for container ships and 1.25 for tankers exceeding 100,000 dwt. Thus the size elasticity of insurance, 1.0, can be a good approximation. Since the forementioned cost items are a very small amount, like 1 percent or at most 10 percent of the capital costs, the effect of each item is modest.

Port costs include port charge, pilotage, custom fees, tonnage tax, stevedorage, tug service, and cargo handling charge. Benford (1968) [Ref. 4] uses the port costs excluding the cargo handling and terminal use charge because it is the same for all alternatives. Kendall (1972) [Ref. 10] accepts the diseconomies of port costs to ship size, but excludes the port costs because of the difficulties in establishing a functional relationship. His model assumes that a fairly constant cost per ton over a limited size exists whereas the significant discontinuities may occur when the ship exceeds a certain size. However Benford, and Jansson and Shneerson use the port costs which are separate from the operating costs. Their study estimates the elasticity, 1.0, which is proportional to ship size. Each port is dealt with as a different size elasticity, but this paper accepts the size elasticity as 1.0. The port costs are composed of various costs due to the different port operation policies.

In Jansson's model the operating costs except fuel at sea and port costs are regressed with respect to the ship size by using a log-linear form. Therefore, the size elasticity of operating costs except fuel and port costs has a range of $0.3 \leq e_2 \leq 0.6$ from Tables 6 and 7.

c. Fuel Costs

Fuel consumption was found to be proportional to the installed horsepower of the ship in the studies of Thorburn (1960), Heaver (1968), Benford (1968), and Goss and Jones (1971) [Refs. 4,6,8]. This implies that if the design speed is held constant as ship size increases, the partial relationship between fuel consumption and size can be described as follows:

$$\text{Fuel consumption} = (\text{deadweight ton})^{2/3}$$

The studies by Heaver (1968), and Goss and Jones (1971) support this relationship. It is noted that no two ships consume fuel at the same rate even in sisterships because the actual physical operation of a vessel, and the level of crew training, as well as hull or machinery condition, are different. Furthermore, despite the drastic changes in fuel costs that have taken place, the size elasticity has stayed very much the same between Table 6 and Table 7. Thus the size elasticity of fuel cost with respect to ship size can be $0.6 \leq e_3 \leq 1.0$.

d. Cargo Costs

If the shipper operates his own ship, the cargo costs must be considered in order to decide the optimum ship size. If the magnitude of cargo cost is negligibly small, this cost category can be assumed zero as in Benford and Jansson's model.

The cargo costs include the invested costs for storing the products carried, operating costs for the facility, and interest cost of the money invested in the cargo during the carrying and storing of the products. Since the costs for the cargo are not discussed in the literature, this model will also assume the cargo cost zero. The size elasticity of cargo cost, 1.0, which is proportional to the ship size, was estimated by Jansson and Shneerson. The cargo costs are different from each port, so that the cargo costs should be calculated separately for each port as well as the port costs. Therefore, the model may use different scale coefficients for each port costs and cargo costs. This model chooses the size elasticity, $e_4 = 1.0$ for port costs as the cargo costs.

e. Summary of the Estimates

The size elasticities of the output capacities (E_1,E_2) and the costs (e_1,e_2,e_3,e_4) of this model can be summarized from Tables 4, 5, 6 and 7 as follows in Table 8.

The reader should be aware that the results in Table 8 come from a variety of different models and some of the empirical results did not have an exceptionally high

TABLE 8

Summary of the Size Elasticities of the Output and Cost

Ship Type	E_1	E_2	e_1	e_2	e_3	e_4
Dry bulk cargo carrier	0.1	1.0	0.7	0.4	0.7	1.0
General cargo ship	0.15	1.1	0.7	0.4	0.7	1.0
Container ship	0.25	1.2	0.85	0.4	0.7	1.0

multiple correlation coefficient, so that the analysis of a shipowner should use his own results based on his experience. Therefore this summary is not conclusive, but can be a guide for deriving his own results.

Recently Jansson and Shneerson proposed that the containers of the liner trade in multiport operation might use the "square-root approximation" which is that $e_i-E_1 = 0.5$, $i = 1,2,4$ for average size elasticity of the handling costs per ton, and that $e_i-E_2 = -0.5$, $i = 1,2,3$ for average size elasticity of the hauling costs per ton-mile. This is based on their estimates that $E_1 = 0.2$, $E_2 = 1.16$, $e_1 = 0.65$, $e_2 = 0.43$, $e_3 = 0.72$, and $e_4 = 1.0$.

If the estimates of e_i, $i = 1,\ldots,4$ and E_i, $i = 1,2$ are inserted explicitly into the total cost function, Equation (15), the final formula for this model will be:

$$TC(S) = \frac{2}{ph_1}(p_1q_1S^{e_1-E_1} + p_2q_2S^{e_2-E_1} + p_4q_4S^{e_4-E_1}) + \frac{D}{\ell h_2}(p_1q_1S^{e_1-E_2} + p_2q_2S^{e_2-E_2} + p_3q_3S^{e_3-E_2}) \quad (16)$$

Since the model assumes the zero cargo cost, the last term drops out from Equation (15). From Equation (16) the handling cost per ton increases with the ship size because the differences e_i-E_1, $i = 1,2,4$ are all positive values, and the hauling cost per ton decreases with the ship size because the differences e_i-E_2, $i = 1,2,3$ are all negative. Therefore the optimum ship size for a given route is obtained by trading off economies of size in hauling operations and diseconomies of size in handling operations. In the next section the model will be verified with data from Gilman's paper [Ref. 5] and the effects of changes in route characteristics and factor costs will be examined.

C. ANALYSIS OF FACTORS AFFECTING THE OPTIMUM SHIP SIZE

The optimum ship size is found at the point where the slopes of the handling and hauling cost curve have the same value; that is, the point of minimum total cost per ton. Figure 2 presents the optimum ship size as determined at the minimum point of the trade-off between the handling cost per ton and the hauling cost per ton. Appendix A provides the computer program to find the optimum ship size with specified route characteristics and a shipowner's economic

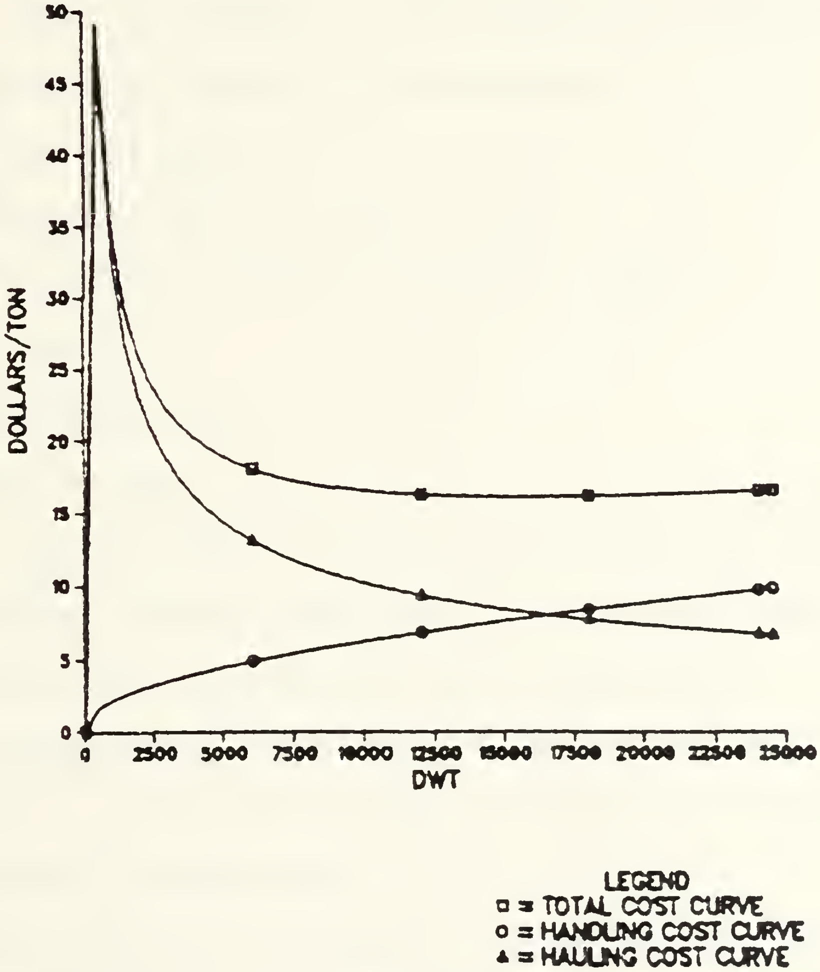

Figure 2. Optimum Ship Size

calculations. Appendix B provides the mathematical formula for economic calculation.

From the previous chapter the range of the estimates vary even for the same type of ship because of the different shipping service such as a liner or tramp, different shipowners, and geographical regions. Once these characteristics are determined by the estimates in a predetermined economic system, how do variations in route characteristics and factor costs affect the optimal ship size?

The effect of changes in the following route characteristics and factor costs will be examined:

round trip distance, D;
cargo handling rate in port i, $p_i h_1$;
cargo balance with hauling capacity, ℓh_2;
capital cost;
operating cost; and
fuel cost at sea;

where p_i is the number of working hours per day in port "i", but this model assumes two base ports with the same characteristic, ℓ is the cargo balance for a given route. The port costs are excluded in the analysis because of the lack of reasonable cost data and correct estimates of the size elasticities of base ports.

Using 14,600 dwt conventional cargo ships as the reference ship from Table 2 in Chapter I, if a shipowner intends to build or charter a similar type of ship, the factor costs can be estimated as:

Capital factor cost for the selected ship is computed from $p_1q_1S^{0.7}$ = \$3,626, then p_1q_1 = \$4.41. This computation is based on the size of the reference ship, S = 14,600 dwt and the value of the estimate, $e_1 = 0.7$. Similarly operating factor cost p_2q_2 = \$39.46 from $p_2q_2S^{0.4}$ = \$1,828, and fuel factor cost p_3q_3 = \$2.31 from $p_3q_3S^{0.7}$ = \$1,899, and the modified port factor cost p_4q_4 = \$0.06 from p_4q_4S = \$900 under the assumption of \$900 port cost per day.

The route characteristics are assumed for the analysis based on Gilman's paper [Ref. 5] in consideration of the current status of the shipping industry in the developing countries:

Round trip distance D = 8,000 miles, cargo handling rate in port of $p_1h_1 = p_2h_1$ = 400 tons per day, and the cargo balance factor $\ell = 1.8$ based on the 0.8 for inbound leg and 1.0 for outbound leg. Using cargo stowage factor 2.85 cubic meters per ton for general cargo, hauling capacity h_2 canbe estimated as $h_2 = 100$ and $\ell h_2 = 180$ because 35.31 cubic feet equals 1 cubic meter.

1. Round Trip Distance

Ship size increases with distance since the increase of D in Figure 2 shifts the hauling cost curve proportionally upward. Therefore the hauling cost curve moves upward, and the minimum point of the total cost curve moves to the right towards a bigger size. Figure 3 and Table 9 show that the

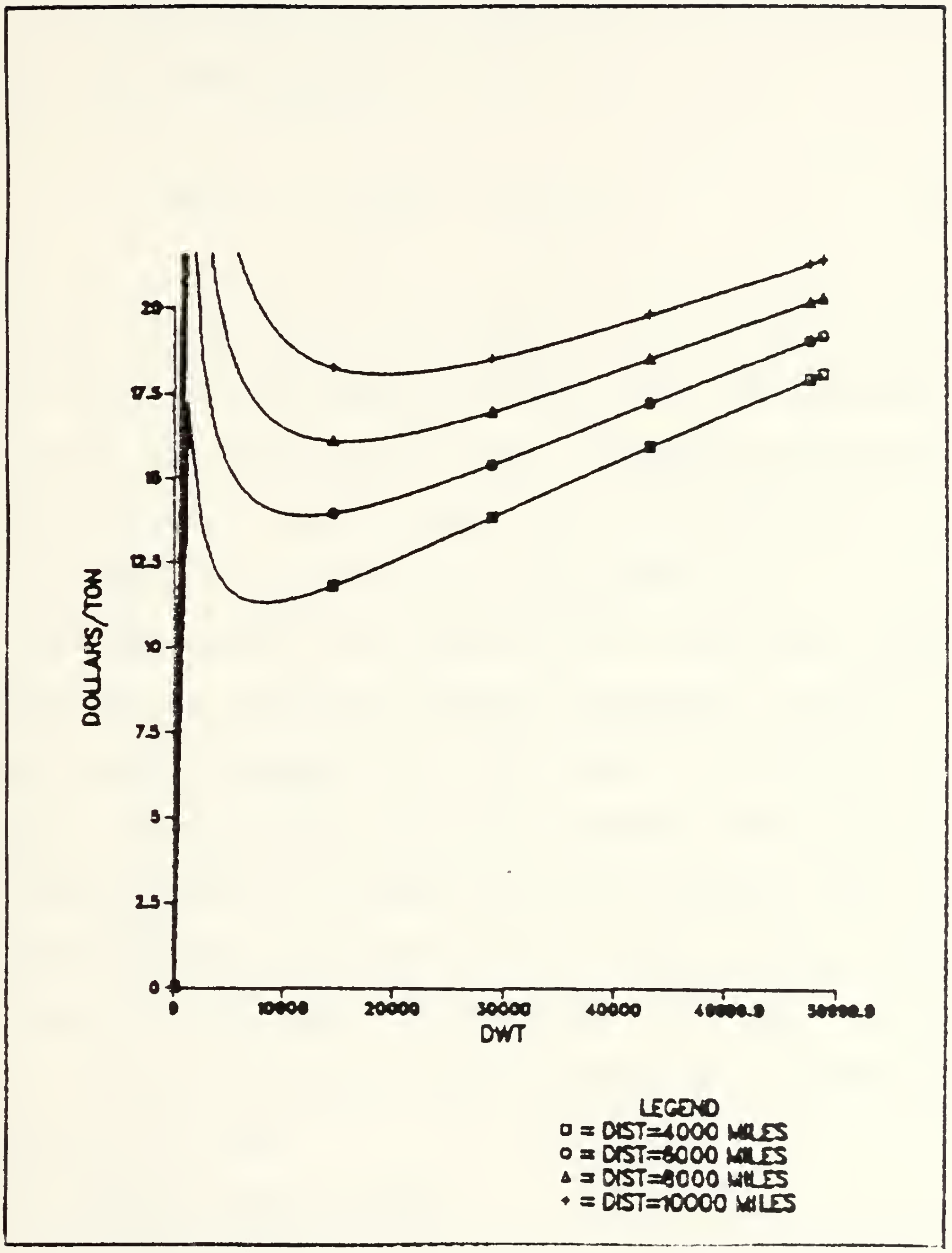

Figure 3. Optimum Ship Size as a Function of Distance

increase of the optimal size is proportional to the increase of the distance. The magnitude of the proportionality depends on the difference between the port costs in handling costs and the fuel cost in the hauling costs of the model.

The cost per ton as a function of the round trip distance D is described as:

$$TC(S) = g_1(S) + Dg_2(S) , \qquad (17)$$

where $g_1(S)$ is the sum of the handling cost per ton and cargo cost per ton, but this model includes only the handling cost, and $g_2(S)$ is the slope of the cost line which is the hauling cost per ton-mile. Given a ship size, cost per ton is a linear function of distance with the slope $g_2(S)$. It is well known that the freight rate per ton of a particular commodity decreases as the transport distance increases. That is, the freight charge increases, but less than in proportion to the distance. Figure 4 shows that the freight curve can be viewed as an envelope that is tangent to four different cost lines of the optimum ship which has 4,000, 6,000, 8,000, and 10,000 miles for D. The longer the distance, the flatter the cost line is. Hence the greater the distance, the larger the optimal ship will be.

2. Handling Rate in Port

An increase in p or h_1 will shift the handling cost curve proportionally downwards so that its slope becomes

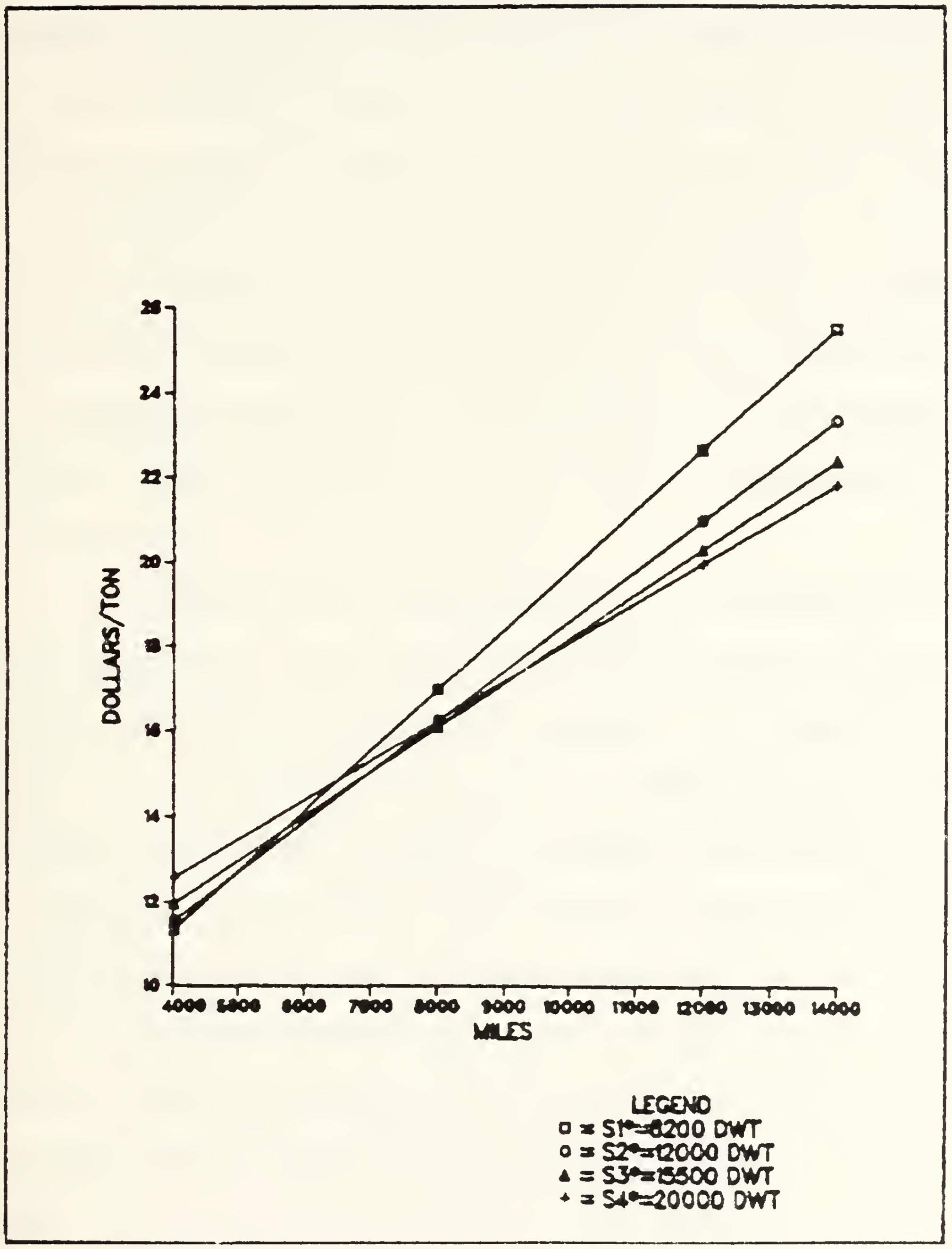

Figure 4. Cost Lines of Given Size S*

flatter; this will move the minimum point to the right in Figure 2. Figure 5 and Table 9 show that the increase of the optimal ship size is proportional to the increase of cargo handling rate, but the total transport cost per ton is reduced conversely to the increase of handling rate. Thus, the high daily costs in port can compensate for the high ton-mile costs at sea by savings in ship time in port.

In Figure 5 the larger the optimal ship size the less the decrease of the minimum total cost will be because of the rapid increase in the port cost. The effect of port costs, however, depends on the magnitude of size elasticity of the port costs and factor proportion in comparison to the other factors.

If a sufficient differential can be established in handling capacity, ships employing sophisticated technologies can be cheaper than conventional vessels. In Table 1 of Chapter I this may be a limitation to improve to two times the present conventional handling capability because there is no such big conventional cargo ship, approximately 25,000 dwt, with more than 1,000 tons per day, except container ships. By changing technology the container ships have increased the handling capability from 1650 to 16,000 tons per day as well as the Ro-Ro ships from over 3000 to 7000 tons per day.

The reason for the wide span of ship sizes on a given trade route, from conventional general cargo liners at

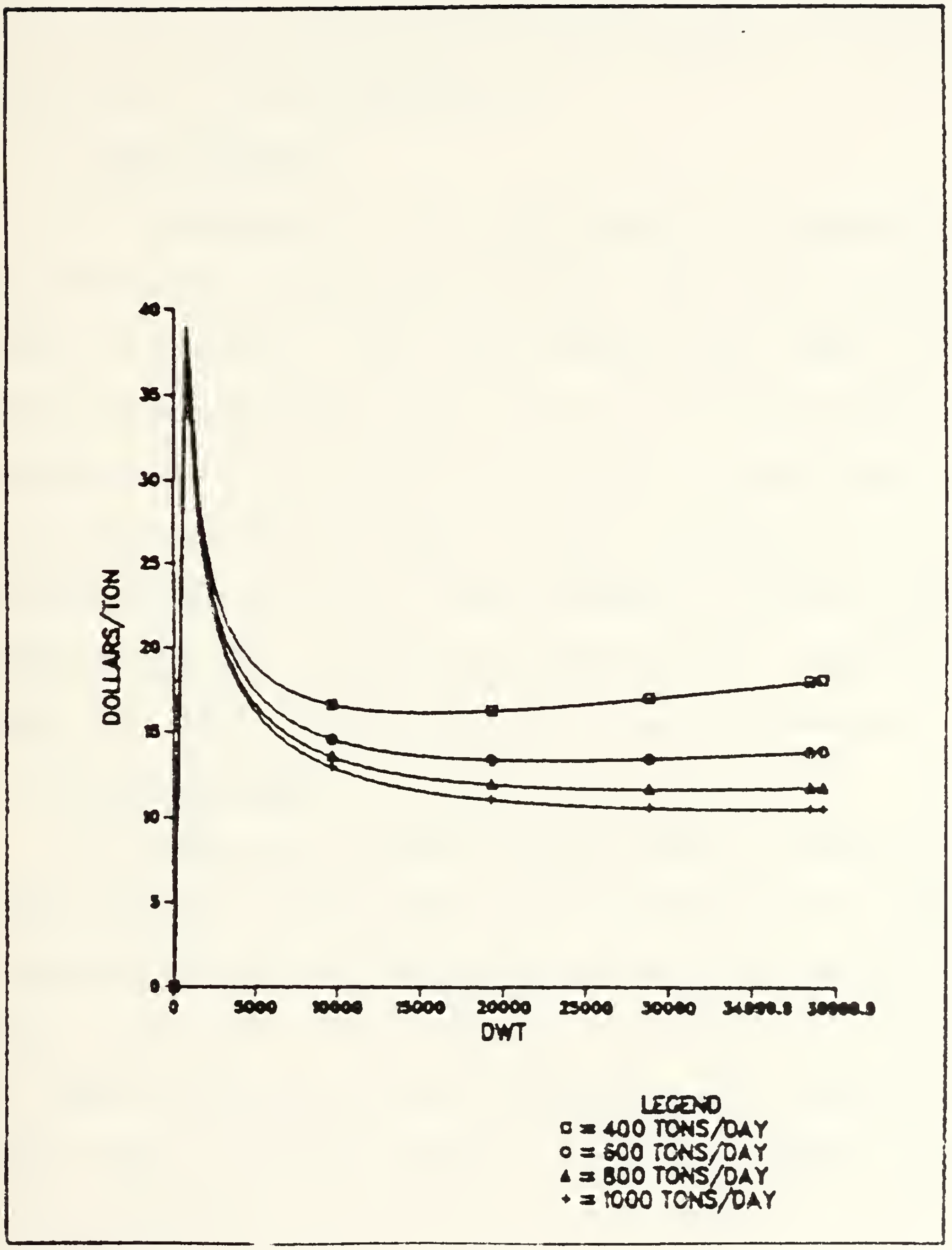

Figure 5. Optimum Ship Size as a Function of Handling Rate

one end of the span to oil tankers some 30 times as big at the other end, can be explained by the very different values of h_1. The other cause may be that the size elasticity E_1 of the handling capacity is higher for oil tankers than for general cargo ships. Hence, the reduction in the handling cost per ton will be balanced by the increase in the hauling cost per ton of the optimum ship.

3. Cargo Balance

An increase in ℓ or h_2 will shift the hauling cost curve downwards and the minimum total cost curve moves to the left in Figure 2. The more balanced the trade is, the smaller the optimal ship size will be. The low cargo balance and large value of the hauling capacity, h_2 will make the bulk carrier or tanker larger. Hence the optimal ship size decreases proportionally to the increase of hauling capacity in addition to the increase of trade balance. Figure 6 presents the effect of the changes in cargo balance.

4. Capital Cost

An increase in capital costs tends to reduce the optimum size of the ship, but the magnitude of the influence is rather weak and the optimum ship size is affected little. However, the effect on the minimum total cost per ton is very high, thus the subsidy of the government will induce a lower freight rate in shipping service. The U.S. Chevron* Company

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*"Shrinking the Oversized Supertanker," The New York Times, 18 July 1980.

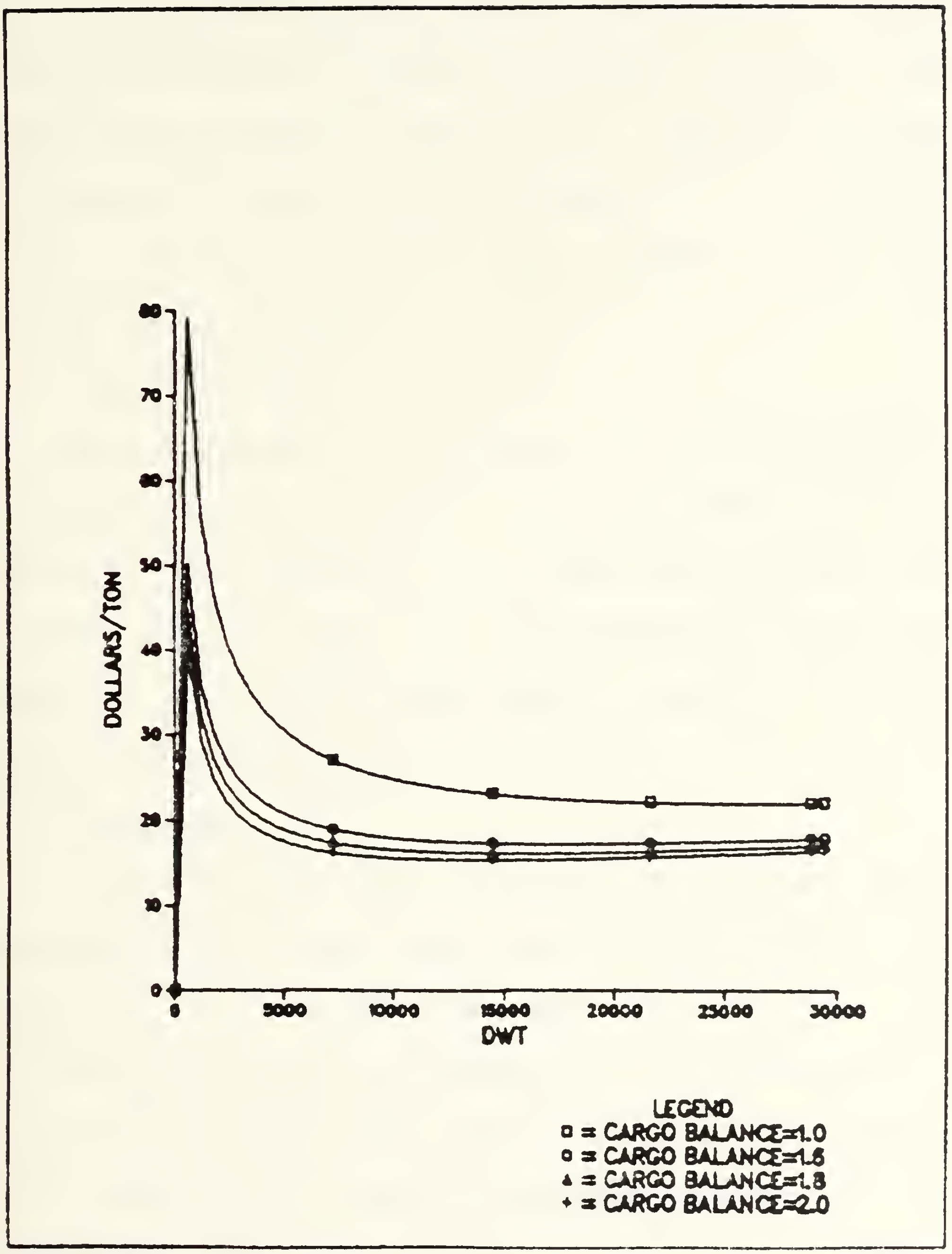

Figure 6. Optimum Ship Size as a Function of Cargo Balance

has reduced their own four 212,000 dwt tankers to 150,000 dwt in 1980 to save a building cost of 37-47 million dollars by cutting the midsection to meet their trade route over San Francisco to Dumai, Sumatura. This shows a four times saving over the new building costs in addition to the lower fuel cost and access to shallow harbors, or harbors with limited cargo and docking facilities. Hence the capital cost gives mild effect to the optimum ship size whereas the total cost per ton has the greatest effect. Figure 7 and Table 9 shows its effect.

5. Operating Cost

The increase of the optimum ship size is less than proportional to the increase of operating cost in Figure 8 and Table 9. The effect in the larger ship becomes smaller than in the smaller ship. The total effects to the optimum ship will be the relative magnitude E_1 and E_2, and factor proportion in the total cost function.

6. Fuel Cost

A rise in fuel cost increases the optimum ship size proportionally since the fuel cost effects only the hauling cost per ton. If the factor proportion of the fuel cost $p_3q_3S^{e_3}$ becomes bigger in comparison with the capital cost $p_1q_1S^{e_1}$, the operating cost $p_2q_2S^{e_2}$, and the port cost $p_4q_4S^{e_4}$, then the fuel cost is the most important determinant of the optimum ship size. In this model the fuel cost is the largest factor proportion and the next is the operating

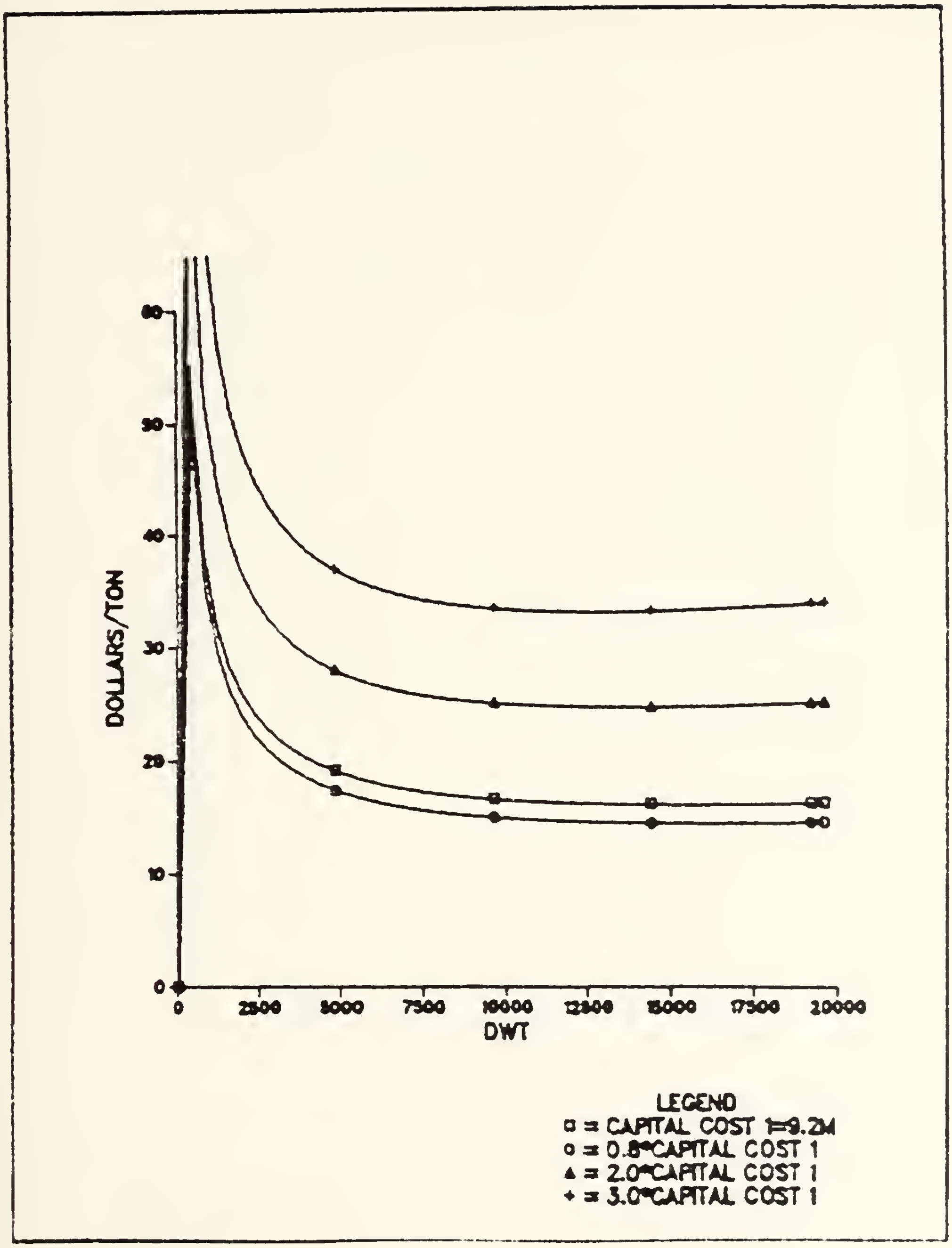

Figure 7. Optimum Ship Size as a Function of Capital Cost

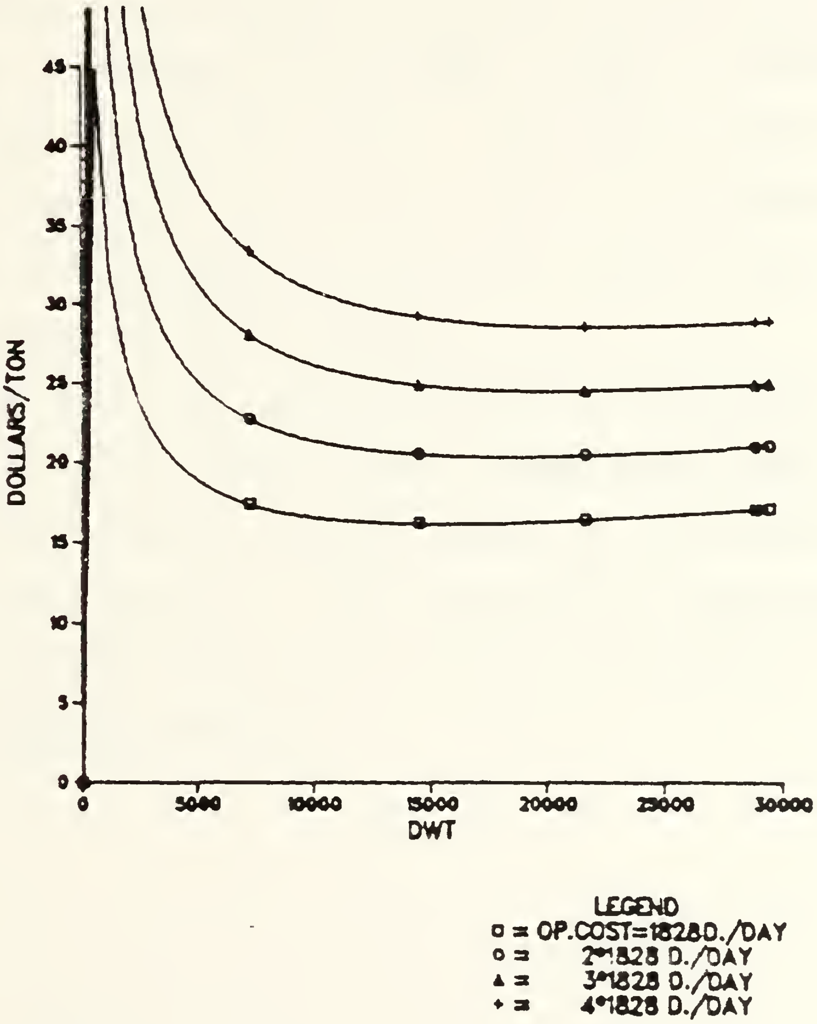

Figure 8. Optimum Ship Size as a Function of Operating Cost

cost. These combined effects have induced Chevron Company to physically reduce the size of their existing ships. The significant savings of capital investment and fuel cost by quarter size of the original one will make substantially reduced total cost per ton. Figure 9 and Table 9 show the proportional change in the optimal ship size.

7. Summary of the Analysis

The major determinants of the optimal size of the ship are the round trip distance and cargo handling rate because the amount of changes in the index is large in comparison with the small changes of the factor. The effect of the change in cargo balance is quite large. This can be explained by the large size difference between the general cargo ship and the bulk cargo carrier or tanker.

The fuel cost affects the size of the optimum ship more than the other factor cost. However the change of the capital cost gives the largest effect in the minimum total transport cost per ton. This indicates the importance of the subsidy from a government for reducing the competitive freight rates in shipping service.

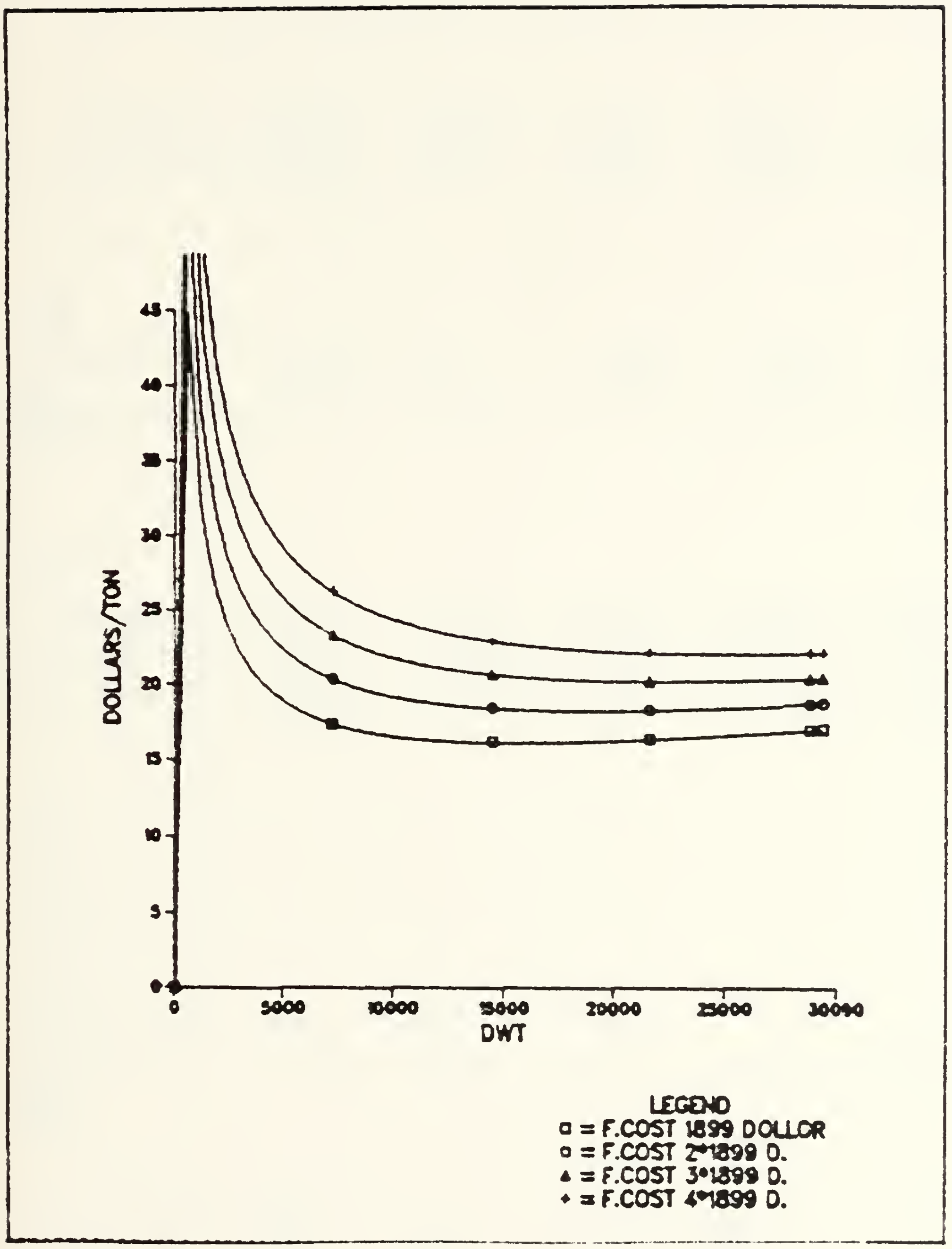

Figure 9. Optimum Ship Size as a Function of Fuel Cost

TABLE 9

Summary of the Computer Outputs

Factors	Index of Factor's Increment*	Optimum Ship Size, S* Size (dwt)	Optimum Ship Size, S* Index of Increment*	Minimum Total Cost, TC(S*) Cost ($)	Minimum Total Cost, TC(S*) Index of Increment*
Round Trip Distance	0.5	8,182	0.53	11.32	0.70
	0.75	11,894	0.77	13.90	0.86
	1	15,495	1	16.11	1
	1.25	19,012	1.23	18.10	1.12
Cargo Handling Rate	1	15,495	1	16.11	1
	1.5	22,463	1.45	13.28	0.82
	2	29,205	1.88	11.60	0.72
	2.5	35,779	2.31	10.46	0.65
Cargo Balance	0.56	26,531	1.71	21.93	1.36
	0.89	17,263	1.11	17.13	1.06
	1	15,495	1	16.11	1
	1.12	14,066	0.91	15.26	0.95
Capital Cost	1	15,495	1	16.11	1
	0.8	16,136	1.04	14.39	0.89
	2	13,653	0.88	24.64	1.53
	3	12,773	0.82	33.11	2.06
Operating Cost	1	15,495	1	16.11	1
	2	18,228	1.18	20.29	1.26
	3	20,338	1.31	24.37	1.51
	4	22,050	1.42	28.39	1.76
Fuel Cost	1	15,495	1	16.11	1
	2	18,642	1.20	18.20	1.13
	3	21,837	1.41	20.14	1.25
	4	25,061	1.62	21.98	1.36

*Index number 1 is the specified characteristics in Section C.

V. CONCLUSIONS

This thesis has demonstrated how a shipowner or charterer might determine the economical size of the ship in a given dense cargo route to minimize his total transport cost per ton of a particular ship. Although the value of the estimates may vary among the type of vessels, type of shipping service as well as different shipping operators, the principle of the model can be applied to any type of ship. Furthermore, the model can be extended to use the comparison of alternatives for ship designs based on the minimum required freight rate which can be defined as the minimum total transport cost per ton.

The model may be justified in the thin trade route with multiports. If the demand imposes a constraint on the maximum feasible ship size, the optimum ship size should be determined simultaneously with the optimal frequency of shipping service. And the model can be improved by using multivariables, such as shaft horsepower, handling rate, speed and size of the ship as independent variables.

APPENDIX A

COMPUTER PROGRAM TO FIND AN OPTIMAL SHIP SIZE

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C      THE PROGRAM IS TO FIND OPTIMJM SHIP SIZE WITH REFERENCE SHIP  C
C      CHARACTERISTICS AND A SPECIFIED ROUTE CHARACTERISTICS BASED   C
C      ON THE COST MODEL FOR CONVENTIONAL CARGO LINER OR MODERN      C
C      CONTAINER SHIP BY CHANGING THE RELEVANT COEFFICIENTS.         C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C      VARIABLE DEFINITION
C      E1,E2             =OUTPUT ELASTICITIES WRT THE SHIP SIZE
C      SE1,SE2,SE3,SE4=COST ELASTICITIES WRT THE SHIP SIZE
C      DWT               =DEADWEIGHT TONNAGE OF THE REFERENCE SHIP
C      CCI,CCA,CCD       =CAPITAL COSTS OF INVESTMENT,ANNUAL CAPITAL
C                         COSTS,CAPITAL COST/DAY
C      R,N               =INTEREST RATE,ECONOMIC LIFE OF THE EXPECTED SHIP
C      OCD,FCD,PCD       =OPERATING COST/DAY,FUEL COST/DAY,PORT COST/DAY
C      DIST              =ROUND TRIP DISTANCE
C      PH1               =HANDLING RATE IN PORT
C      L,H2              =CARGO BALANCE,HAULING CAPACITY OF THE SHIP
C      TM1,TM2           =HANDLING COST/TON IN PORT,HAULING COST/TJNAT SEA
C      TC                =TJTAL COST/TONFOR THE EXPECTED SHIP
       IMPLICIT REAL*8(A-H,O-Z)
       REAL*8 L,LH2,XDAT(101),YDAT(101),HAND(101),HAUL(101),
      1       THETA(100)
       REAL*4 XDATA(101),YDATA(101),HANDC(101),HAULC(101)
       S=1000.D0
       D=1.D0
C      TO FIND MINIMUMUM TOTAL COST PER TON TO GET OPTIMJM SHIP SIZE
       CALL FUN(S,TM1,TM2,TC)
       CALL SEARCH(S,D,TC)
C      GRAPHS TO FIND OPTIMUM SHIP SIZE
       XDAT(1)=0.0D0
       YDAT(1)=0.0D0
       HAND(1)=0.0D0
       HAUL(1)=0.0D0
       DO 10 I=1,50
            XDAT(I+1)=XDAT(I)+500.D0
            X=XDAT(I+1)
            CALL FUN(X,TM1,TM2,Y)
            YDAT(I+1) =Y
            HAND(I+1) =TM1
            HAUL(I+1) =TM2
 10    CONTINUE
       WRITE(6,300) (XDAT(I),YDAT(I),HAND(I),HAUL(I),I=1,50)
 300   FORMAT(6X,4F12.4)
       XDATA(1)=0.0
       YDATA(1)=0.0
       HANDC(1)=0.0
       HAULC(1)=0.0
       DO 20 I=1,50
```

```
          XDATA(I)=XDAT(I)
          YDATA(I)=YDAT(I)
          HANDC(I)=HAND(I)
          HAULC(I)=HAUL(I)
 20   CONTINUE
C     TO USE TEKTRON PLOT
C     CURVE-1
      CALL TEK618
      CALL PLOTD(XDATA,YDATA,50,.FALSE.,'LINLIN','TOTAL COST CURVE   $'
     |,'FIG.2 OPTIMUM SHIP SIZE$','DWT$','DOLLARS/TON$')
C     CURVE-2
      CALL PLOTD(XDATA,HANDC,50,.FALSE.,'LINLIN','HANDLING COST CURVE$'
     |,' $','DWT$','DOLLARS/TON$')
C     CURVE-3
      CALL PLOTD(XDATA,HAULC,50,.TRUE.,'LINLIN','HAULING COST CURVE $'
     |,' $','DWT$','DOLLARS/TON$')
      CALL DONEPL
      STOP
      END
      SUBROUTINE FUN(S,TM1,TM2,TC)
C     TO COMPUTE TOTAL COST PER TON
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 L,LH2
C     ENTER INPUT DATA
      E1=0.15
      E2=1.1
      SE1=.7
      SE2=.4
      SE3=.7
      SE4=1.0
C     DATA FOR REFERENCE SHIP
      DWT=14600.DO
      CCI=9200000.DO
      R  =.12
      N  =18
      CCA=CCI*R/(1.-(1.+R)**(-N))
      CCD=CCA/350.DO
      OCD=1828.DO
      FCD=1899.DO
      PCD=900.DO
C     SPECIFIED ROUTE CHARACTERISTICS
      DIST=8000.DO
      PH1 =400.DO
      L   =1.8DO
      H2  =100.DO
      LH2 =L*H2
C     TO COMPUTE FACTOR COSTS PER TON IN PORT AND AT SEA
      P1Q1=CCD/(DWT**SE1)
```

```
      P2Q2=OCD/(DWT**SE2)
      P3Q3=FCD/(DWT**SE3)
      P4Q4=PCD/(DWT**SE4)
C     TO COMPUTE TOTAL FACTOR COST PER TON IN PORT AND AT SEA
      TC1=P1Q1*S**(SE1-E1)+P2Q2*S**(SE2-E1)+P4Q4*S**(SE4-E1)
      TC2=P1Q1*S**(SE1-E2)+P2Q2*S**(SE2-E2)+P3Q3*S**(SE3-E2)
C     TO COMPUTE TOTAL COST PER TON
      TM1=2.D0*TC1/PH1
      TM2=DIST*TC2/LH2
      TC =TM1+TM2
      RETURN
      END
      SUBROUTINE SEARCH(S,D,TC)
C     TO BRACKET MINIMUM AND TAKE STEP TO GET MINIMUM VALUE GTHETA
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 L,LH2,THETA(100)
      NMAX=50
      DEL =0.0001D0
      TOW =(1.D0+DSQRT(5.D0))*.5D0
      TOL =0.001D0
      NTIMES=0
 15   W=S+DEL*D
      THETA(1)=0.0D0
      TCO=TC
      CALL FUN(W,TM1,TM2,TCN)
      THETAL=THETA(1)
      THETA(2)=DEL
      THETAR=THETA(2)
      NTIMES=NTIMES+1
      IF (NTIMES.EQ.2) GO TO 45
          IF(TCN.GT.TCO) GO TO 100
C     CONTINUE SEARCH IN THE D-DIRECTION
 45   NNTIME=3
 25   DEL=TOW*DEL
      DD=DEL*D
      W =S+DD
      TCO=TCN
      THETAL=THETA(NTIMES)
      NTIMES=NTIMES+1
      THETA(NNTIME)=DEL
      THETAR=THETA(NNTIME)
      CALL FUN(W,TM1,TM2,TCN)
      NNTIME=NNTIME+1
      IF (TCN.GT.TCO) GO TO 200
          IF (NTIMES.LT.NMAX) GO TO 25
              GO TO 500
C     REVERSE SEARCH DIRECTION
 100  D=-D
```

```
      GO TO 15
C     BEGIN GOLDEN SECTION SEARCH
 200  DIFF=THETAR-THETAL
      SRT =THETAL+DIFF/TOW
      SLT =THETAL+(THETAR-SRT)
      W=S+SLT*D
      Z=S+SRT*D
      CALL FUN(W,TM1,TM2,TCL)
      CALL FUN(Z,TM1,TM2,TCR)
      NN=0
 600  IF (TCL.LT.TCR) GO TO 400
         NN=NN+1
         THETA(NN)=SRT
         DIFF=DABS(THETAR-SLT)
         THETAL=SLT
         SLT   =SRT
         SRT   =THETAL+(THETAR-SLT)
         W=S+SLT*D
         Z=S+SRT*D
         CALL FUN(W,TM1,TM2,TCL)
         CALL FUN(Z,TM1,TM2,TCR)
         FTHETA=THETA(NN)
         IF (DIFF.LT.(DABS(TOL))) GO TO 700
             GO TO 600
 400  NN=NN+1
      THETA(NN)=SLT
      DIFF=DABS(SRT-THETAL)
      THETAR=SRT
      SRT=SLT
      SLT=THETAL+(THETAR-SRT)
      W=S+SLT*D
      Z=S+SRT*D
      CALL FUN(W,TM1,TM2,TCL)
      CALL FUN(Z,TM1,TM2,TCR)
      FTHETA=THETA(NN)
      IF (DIFF.LT.(DABS(TOL))) GO TO 700
         GO TO 600
 500  WRITE(6,1000)
      GO TO 800
 700  SS=S+FTHETA*D
      CALL FUN(SS,TM1,TM2,TCPT)
      WRITE(6,1100) SS,TCPT
 800  CONTINUE
1000  FORMAT('1'/6X,'THIS COST FUNCTION APPEARS TO BE UNBOUNDED')
1100  FORMAT('1'/6X,'OPTIMUMUM SHIP SIZE S*            ',F20.4,2X,'DWT'
     *           /6X,'MINIMUM TOTAL COST PER DWT AT S*',F20.4,2X,'$')
      RETURN
      END
```

APPENDIX B

MATHEMATICAL FORMULA FOR DAILY FACTOR COSTS

To compute the long run capital cost of the present worth, the annual capital cost can be formulated using the annuity formula which converts the capital cost into a constant annual cost:

$$\text{annual capital cost} = \frac{P}{CR}\,, \qquad (1)$$

where the initial investment is P, capital recovery factor $CR = \frac{r}{(1+r)^n - 1}$ with shipowner's interest rate r and the life of the project n.

Both capital cost and operating cost except fuel have been expressed on an annual basis. The divisor for daily cost in Equation (1) must be less than 365 days since the ship spends some time each year under repair. Usually 350 is taken, not because these costs do not carry on during a repair period, but because the opportunity cost of ship's time is calculated. The greater the repair time, the lower the denominator will be and hence the greater the opportunity cost must be:

$$\text{daily capital cost} = \frac{P}{350CR} \qquad (2)$$

To compute the long run operating cost of the present worth, the labor costs per year are treated separately because it is assumed that they increase by 3 percent per year in real terms. The present value of such a geometrically growing time series is:

$$PV = W\left[\frac{1 - \left(\frac{1+g}{1+r}\right)^n}{r-g}\right] \qquad (3)$$

where W is the initial labor cost, g is the annual growth rate of 0.03, and r is the rate of discount. This present value can then be divided by the appropriate annuity factor to give the long-term opportunity cost of labor costs spread over the entire life of the ship:

$$\text{annual wage cost} = \frac{W}{CR}\left[\frac{1 - \left(\frac{1+g}{1+r}\right)^n}{r-g}\right] . \qquad (4)$$

Since the other operating costs are usually available on an annual basis, these costs can be calculated by using an index of factor prices, if necessary, as well as the fuel cost.

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